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A MORE SYSTEMIC APPROACH TO DECISION-MAKING REGARDING REFRIGERANT FLUIDS CREATION OF THE TEWI+S+R INDICATOR

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Abstract: The cold chain is responsible for 26-34% of global emissions, and within this chain is refrigeration. The choice of more sustainable refrigerants is essential for decarbonization. The TEWI (Total Equivalent Warming Impact) indicator has become a quick and important tool for measuring decarbonization levels, but this indicator is limited to energy efficiency associated with emissions. A new indicator is proposed, TEWI+S+R, which includes "S" for safety and "R" for reliability. This means that the choice of refrigerant is not limited to efficiency and emissions, allowing for a broader view in decision-making. Situations were simulated in a frozen food rack for two countries with different energy matrices, and the best result was the R-32 refrigerant for both countries. In other words, refrigerants with medium environmental impact may be viable as a solution in the cold chain.
Keywords: Carbon emissions, Energy, Food chain, TEWI.

INTRODUCTION

Food chains are crucial to modern life. They enable the safe production, storage, and transportation of food, ensuring consumers' confidence in the quality of the products they purchase and consume. However, these chains require large amounts of energy to keep food at the right temperature, resulting in global greenhouse gas (GHG) emissions.

Due to global warming, the world is experiencing higher temperatures. Between 2012 and 2021, global average near-surface temperatures were 1.11 to 1.14 K higher than pre-industrial levels. This makes the last decade the warmest on record. The member countries of the United Nations Framework Convention on Climate Change (UNFCCC) have committed to the Paris Agreement, which aims to limit global temperature rise by 2050 to less than 2 K above pre-industrial levels, with the ideal goal of restricting the increase to less than 1.5 K (European Environment Agency, 2023).

Refrigeration plays a vital role in building safe, sustainable, and resilient food chains. The International Institute of Refrigeration (IIR, 2020) estimates that 778 million tons of food are preserved by refrigeration globally each year. However, ideally, 1,661 million tons should be refrigerated, revealing a significant lack of access to refrigeration systems. About 13% of the food produced worldwide is lost due to a lack of adequate refrigeration; if it were properly refrigerated, it could feed 950 million people per year (Dupont, El Ahmar, and Guilpart, 2020). In low-income countries, most food is lost at the beginning of the chain due to logistical deficiencies, lack of refrigeration, and improper handling. In high-income countries, waste occurs mainly at the end of the food chain, by the consumer. Reducing food loss and waste is essential, as it not only reduces carbon emissions but also increases the availability of food for consumption.

In addition to direct emissions, the food chain generates significant emissions due to the energy used to operate refrigeration systems, transport food, and maintain heating, ventilation, and air conditioning (HVAC) systems. These emissions also come from the refrigerant used in equipment, which, no matter how well installed and maintained, will eventually leak. Refrigeration often consumes the most electricity in food chains, standing out as an area with great opportunities to reduce energy consumption and carbon emissions. Within this chain, the so-called "cold chain" is crucial. In a world that increasingly values decarbonization, quality of life, and reliability, it is essential to develop an index that associates decarbonization and efficiency with safety and reliability.

STATE OF THE ART

After Brazil joined the Montreal Protocol in 1990, in 2009 the National Seminar "Government and Society on the Way to Eliminating HCFCs" began developing the Brazilian Program for the Elimination of HCFCs (PBH). This document defines the guidelines and actions for Brazil to meet the targets for eliminating the consumption of HCFCs (hydrochlorofluorocarbons). In the air conditioning and refrigeration sector, the program establishes that by 2040, the consumption of HCFCs must be completely eliminated. With the Kigali Amendment, new deadlines have been set for the elimination of HFCs, making it necessary to deepen knowledge about technologies with less environmental impact. The market trend is to transition to natural refrigerants, such as ammonia (R-717), carbon dioxide (R-744), and hydrocarbons, which, despite having better GWP (*Global Warming Potential)* ratings, can be toxic, flammable, or operate only under high pressures, requiring stricter inspections and the adoption of appropriate safety measures and standards (Gov.ibama, 2024).

Environmental concerns have become the driving force for optimizing green designs through increased energy efficiency, research into new refrigerants, and efficient use of existing systems. The climate system has always been influenced by humans, so it is crucial to create transparent and easy-to-use methods when designing an energy system with low environmental impact. The environmental metrics used in the refrigerant selection process are GWP and TEWI, which will be explained below. Each metric aims to quantify the impact of refrigerants on global warming, but their use can lead to different conclusions (Santos, et al., 2022).

GLOBAL WARMING POTENTIAL – GWP

GWP is the most widely used environmental metric. It is an index that compares the impact on global warming of a greenhouse gas emission relative to a proportional emission of CO_2. The impact is estimated over a given period of time. A 100-year time horizon is the most commonly used and is usually assumed when no information on the time horizon is given. GWP is an easy-to-use metric, as the lower the GWP, the lower the contribution of a substance to global warming.

TOTAL EQUIVALENT WARMING IMPACT – TEWI

TEWI is a metric of the global warming impact of equipment based on total emissions related to greenhouse gases during equipment operation and the disposal of operating fluids at the end of their useful life. TEWI takes into account both direct emissions and indirect emissions produced through the energy consumed in the operation of the equipment. TEWI is measured in kilograms of carbon dioxide equivalent (kg $_{CO_2e}$) (Santos, et al., 2023).

TEWI is calculated by adding two parts together, which are:

1. Direct Emissions - Refrigerant released during the equipment's useful life, including unrecovered losses during final disposal;

2. Indirect Emissions - The impact of $_{CO_2}$ emissions from fossil fuels used to generate the electricity that is used to operate the equipment throughout its lifetime.

One of the actions to create a system simulation is to understand the progress of refrigerants, their evolution, which is based on four important milestones (Webarcondicionado, 2024):

- 1st Generation (1834~1930) - Solvents, volatile liquids, or any substances that functioned as refrigerants, such as ethers, ammonia (R-717), methyl chloride (R-40), sulfur dioxide (R-764), among others;

- 2nd Generation (1931–1990) – Focused on safety and durability, the most commonly used fluids were CFCs (chlorofluorocarbons), HCFCs (hydrochlorofluorocarbons), HFCs (hydrofluorocarbons), ammonia, and water (R-718);
- 3rd Generation (1991~2010) – The era that set out to reduce the impacts on the ozone layer. After the Montreal Protocol, HCFCs were used for transition, and there was an increase in the use of HFCs, ammonia, water, hydrocarbons, and carbon dioxide (R-744);
- 4th Generation (2010 onwards) – Inclusion of zero ODP (Ozone Depletion Potential) fluids, high efficiency and low environmental impact such as HFOs (hydrofluoroolefins) and increased use of low GWP fluids such as ammonia, carbon dioxide, hydrocarbons, and water.

MONTREAL PROTOCOL

The Montreal Protocol is an international treaty aimed at protecting the ozone layer by eliminating the production and consumption of ODS (Ozone Depleting Substances). The Protocol has the positive aspect of being updated through amendments, thus allowing it to adapt to scientific, technological, and social advances in the sector. Following the guidelines of the Montreal Protocol, a schedule was created for the reduction and subsequent elimination of HCFC consumption, as shown in the table below (Gov.mma, 2023).

YEAR	STAGE
2013	Freeze on HCFC consumption and production based on average consumption between 2009 and 2010
2015	10% reduction in consumption
20	35% reduction in consumption
2025	67.5% reduction in consumption
2030	97.5% reduction in consumption*
2040	100% reduction in consumption

Note: Residual consumption (2.5%) may only be used for the service sector.

Table 1 - Schedule established by the Brazilian HCFC Phase-out Program (PBH) under the Montreal Protocol (Gov.mma, 2023).

In January 2019, the Kigali Amendment came into force, aiming to phase out HFCs (hydrofluorocarbons), which were developed as an alternative to gases banned by the Montreal Protocol. Although HFCs do not destroy the ozone layer, they have a very high global warming potential. The schedule presented in the Kigali Amendment is shown below (Kigali, 2024).

YEAR	STAGE
2024	Freeze on HFC consumption and production based on average consumption between 2020 and 2022
2029	10% reduction in consumption
2035	30% reduction in consumption
2040	50% reduction in consumption
2045	80% reduction in consumption

Table 2 - Kigali Amendment Timeline for HFCs (Kigali, 2024).

For analysis purposes, the main characteristics of synthetic and natural refrigerants are presented in the table below.

Refrigerants	R22	R404A	R507A	R134a	R410A	R407C	R422D	R427A	R717	R744	R290	R1270
Natural Substance	No	No	no	no	no	no	no	no	yes	yes	yes	yes
Trade name	-	-	-	-	-	-	Isceon MO29	FX100	Ammonia	Carbon Dioxide	Propane	Propylene
Manufacturer	Various	Various	Various	Various	various	various	DuPont	Arkema	various	various	various	various
Chemical composition	CHF2CL	R143a/R125/R134a	R143a/R125	CF-3CH2F	R32/R125	R32/R125/R134a	R125/R134a/R600a	R32/R125/R143a/R134A	NH3	CO2	C3H8	CO2
Ozone Depletion Potential (ODP)* Ozone (ODP)*	0.05	0	0	0	0	0	0	0	0	0	0	0
Global Warming Potential (GWP)**	1500	3260	3300	1300	1725	1525	2230	1830	0	1	3	3
Glide temperature (K)	0	0.7	0	0	0.2	7.4	4.5	7.1	0	0	0	0
Boiling Point (°C)	-40.86	-47	-47	-26.07	-51	-40	-45	-43	-33	-57 (sulimb.)	-42	-47.7
Critical Temperature (°C)	96.15	73	71	101.15	72	86	81	87	133	31	96.7	92.4
Critical Pressure (bar)	50.54	37.8	37.9	40.67	49.5	46.5	39.08	44	113.5	73.8	42.48	46.65
Flammability	No	No	No	No	no	no	no	no	low	no	high	high
Toxicity	low	low	low	low	low	low	low	low	high	low	low	low
Type of lubricating oil ***	MO/AB/MO+AB	POE	POE	POE	POE	POE	MO/AB/POE	MO/AB/POE	MO/PAO	POE	MO/PAO/POE	MO/PAO/POE
Type of application***	HT/MT/LT	MV/LV	MT/LT	HT	HT	HT	HT/MT/LT	HT/MT/LT	HT/MT/LT (Indirect Systems)	MT AND LT	HT/MT/LT (Indirect Systems)	MT/LT (Indirect Systems)
Relative Cost Refrigerant/Kg	1	3	4	2	4	3	8	10	0.1	0.1	0.1	0.1
Energy Efficiency Relative Average (%)	100	99	102	97	95	100	95	95	105	120 (subcritical)	102	101
Equipment (Retrofit)	-	New	New	New	New	New	Existing	Existing	New	New	New	New

Table 3 - Characteristics of synthetic and natural refrigerants (Gov.MMA, 2011).

**Ozone Depletion Potential (ODP)*: this index is based entirely on the reference of refrigerant gas R11 (100%). For example, R22 has an ODP = 0.05, meaning it has an ozone depletion potential of 5% compared to R11.

Global Warming Potential* (*GWP*): this is an index that compares the warming effect produced by gases in the atmosphere over time (usually 100 years) in relation to similar amounts of $_{CO_2}$(by weight). For example, 1 kg of R404A released into the atmosphere produces the same global warming effect as 3260 kg of $_{CO_2.}$This is the same amount that a popular car would pollute the atmosphere by driving for two years in the city of ***São Paulo.

*** Type of Application: HT = High evaporation temperature (air conditioning), MT = Medium evaporation temperature (cooling system), LT = Low evaporation temperature (freezing system).

For the development of this study, simulations and indices were created to facilitate the replication of solutions.

The kg CO_2/TR index, created due to the difficulty of obtaining data on the effective installed capacity in the country, so that it is possible to simulate scenarios, understand opportunities, and replicate solutions, demonstrates how each system, with its respective refrigerant, acts on global warming according to the thermal load served.

In addition to the GWP issue, Ashrae separates refrigerants into flammability and toxicity classifications, as shown in the figure below (Ashrae 34, 2010):

The best safety rating is class A1 (non-toxic and non-flammable), and the worst is class B3 (toxic and flammable).

MATERIALS AND METHODS

The *Total Equivalent Warming Impact* (TEWI) calculation considers energy consumption over the useful life, including indices such as COP, IPLV, and NPLV in useful life simulations, as well as direct and indirect emissions. However, it ignores crucial aspects such as flammability, toxicity, and reliability, factors that must also be considered when evaluating the best refrigerant option for a specific application. Reliability, for example, can be affected by the compressor discharge temperature and temperature glide. Therefore, TEWI alone is not a comprehensive measure (Santos et al, 2022).

In environments such as supermarkets, toxicity and flammability are as important as energy consumption and emissions, along with reliability. Thus, an expanded index, TEWI-S+R, is proposed, where S stands for "SAFETY" and R stands for "RELIABILITY," which can provide a better classification of refrigerants for customers, considering all these factors.

A survey was conducted with 10 refrigeration teachers from Fapro-ETP, addressing the following questions:

On a scale of 1 to 5, how relevant are the following factors: energy consumption and sustainability, safety, and reliability?

If we were to measure safety, what would be the index for each category of refrigerants, from A1 to B3?

How important would the compressor discharge temperature and temperature glide be?

Based on the weighted average of the responses, the following results were obtained:

Safety Index (S):

The safety rating (S) is indicated as follows:

- Class A1: Maximum score = 1.
- Class A2L: Score = 0.8.
- Class B1: Score = 0.6.
- Class B2L: Score = 0.4.
- Classes A2 and A3: Score = 1 if less than 150 grams and Score = 0.4 if greater than 150 grams.
- Classes B2 and B3: Score = 0.

These values are justified by the significant difference in ignition energies. For example,

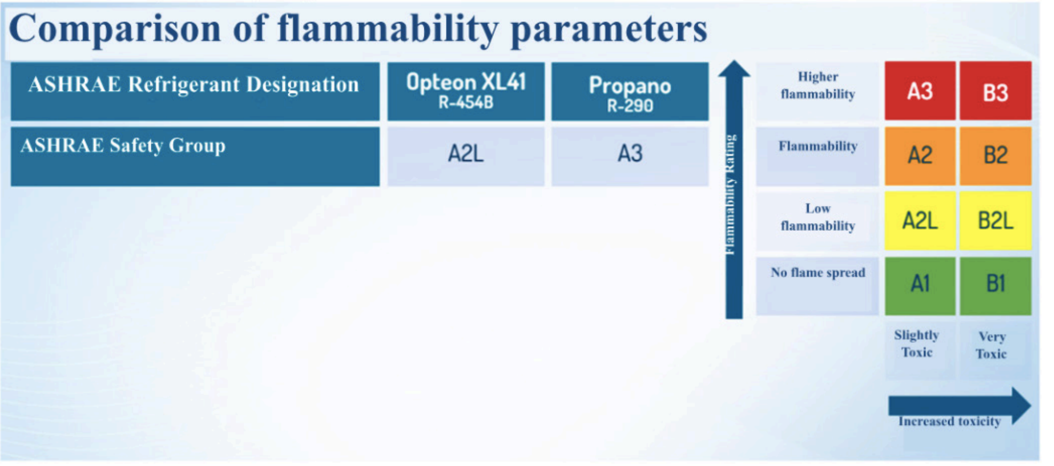


Figure 1 – Comparison of flammability parameters

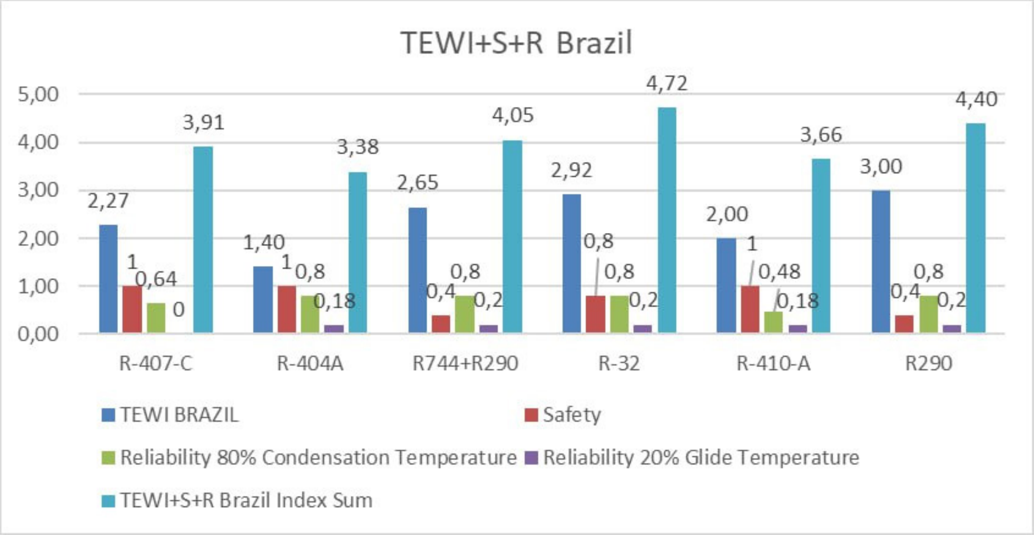
The following results were obtained:

Characteristics	R-407-C	R-404A	R744+R290	R-32	R-410-A	R290
COP	1.54	1.36	1.37	1.61	1.502	1.558
Discharge temp. °C (when subcritical worst situation)	95.6	71.9	62.4	85.18	104.3	75.4
Energy Consumed (kWh)	102,578.8	115,987.6	114,658.4	97,761	105,005.6	101,194.8
Suction line diameter (mm)	82.5	78.1	64.5	67.93	62	80.6
Mass displacement (kg/s)	0.31	0.4781	0.24	0.349	0.3	0.18
Refrigerant charge (kg)	11.2	16.07	6.3	5.712	14.07	4.48
TEWI Direct (kgCO2/lifetime) USA	54691.84	176,474.3	24.87	10,795.68	82,258.85	37.63
Indirect TEWI (kgCO2/lifetime) USA	844,633.84	955,041.9	944,097.27	804,964.1	864,616.1	833,238
TEWI Total (kgCO2/lifetime) USA	899,325.68	1,131,516	944,122.14	815,759.8	946,875	833,275.6
TEWI Direct (kgCO2/lifetime) Brazil	54,691.8	176,474.3	24.87	10,795.68	82,258.85	37,632
Indirect TEWI (kgCO2/lifetime) Brazil	180,538.69	204,138.2	201,798.78	172,059.4	184,809.9	178,102.8
TEWI Total (kgCO2/lifetime) Brazil	235,230.53	380,612.5	201823.66	182,855	267,068.7	178,140.5
Useful life years	20	20	20	20	20	20
Annual leakage rate (%)	0.125	0.125	0.125	0.125	0.125	0.125
GWP AR-4 (when weighted average subcritical cycle)	1744	392	1.41	675	2088	3
Recycling Index (%)	0.7	0.7	0.7	0.7	0.7	0.7
Carbon Emission Index per kW Brazil (kg/kW)	0.088	0.088	0.088	0.088	0.088	0.088
Carbon Emission Index per kW USA (kg/kW)	0.4117	0.4117	0.4117	0.4117	0.4117	0.4117
Ashrae class (worst case scenario)	A1	A1	A3	A2L	A1	A3
Temperature Glide (K)	7.4	0.8	0	0	0.1	0

Table 4 – Characteristics of each fluid.

	R-407-C	R-404A	R744+R290	R-32	R-410-A	R290
TEWI Brazil	2.27	1.40	2.65	2.92	2.00	3.00
Safety	1	1	0.4	0.8	1	0.4
Reliability 80% Condensation Temperature	0.64	0.8	0.8	0.8	0.48	0.8
Reliability 20% Glide Temperature	0	0.18	0.2	0.2	0.18	0.2
Sum TEWI+S+R Index Brazil	3.91	3.38	4.0	4.72	3.66	4.40

Table 5 – TEWI+S+R Index Brazil



Graph 1 – TEWI+S+R Brazil

	R-407-C	R-404A	R744+R290	R-32	R-410-A	R290
TEWI-USA	2.72	2.51	2.65	3	2.58	2.94
Safety	1	1	0.4	0.8	1	0.4
Reliability 80% Condensation Temperature	0.64	0.8	0.8	0.8	0.48	0.8
Reliability 20% Glide Temperature	0	0.18	0.2	0.2	0.18	0.2
TEWI+S+R USA	4.36	4.49	4.05	4.8	4.24	4.34

Table 6 – TEWI +S+R USA

an A2L fluid such as R454-B requires an ignition energy nearly 1000 times greater than R-290 (propane). In addition, NH3, classified as B2L, is toxic and slightly flammable, while R-290 is non-toxic but highly flammable, although acceptable in doses less than 150 grams according to NBR 16069.

Reliability Index (R):

The reliability of a system is strongly influenced by the discharge temperature of the refrigerant. High discharge temperatures (>150°C) can lead to oil decomposition, affecting the durability of the system. In addition, high temperature glide values can cause maintenance problems if professionals are not qualified, and if there is a leak in a "blend," there will be a greater leak of one of the fluids (since they are mixtures), which can generate undesirable imbalances and changes in performance (Ahrinet, 2024) (Li et al, 2023).

The formula for the reliability index (R) is described as: R=(0.8×Discharge Temperature Factor)+(0.2×Temperature Glide Factor).

Discharge Temperature Factor:

- Less than 90°C: 1.
- Between 90°C and 100°C: 0.8.
- Between 100°C and 120°C: 0.6.
- Between 120°C and 130°C: 0.4.
- Above 130°C: 0.

Temperature Glide Factor:

- Zero Glide: 1.
- Up to **1°C: 0.9**.
- Between **1°C** and **2°C: 0.8**.
- Between **2°C** and **4°C: 0.6**.
- Between **4°C** and **6°C: 0.4**.
- Above 6°C: 0.

When comparing refrigerants, the lowest TEWI will have a weight of 3, while the other fluids will have a proportional weight. The final TEWI-S+R formula is described as:

TEWI + S + R = (3×Fator TEWI) + Fator Safety + Fator Reliability (1)

The refrigerant that obtains a score closest to 5 will certainly be the best ecological, safe, and reliable option.

It is important to note that the $kgCO_2$/kWh equivalent varies from country to country, which means that an ideal solution for one country may not be the best for another.

ANALYSIS AND DISCUSSION

For the initial simulation, a cooling load of 45 kW was used, which will be simulated in two countries, Brazil and the United States, with six refrigerant options:

- R-134 A.
- R 404 A.
- R 744 + R 290 (subcritical cascade).
- R 744 + R 32.
- R 32.
- R 410A.

Simulations were performed to determine energy consumption using Coolpack+IPU and Solkene software. The following characteristics were used in all options:

- Thermal load = 45 kW.
- Evaporation Temperature = -30ºC.
- Total Superheat = 8ºC.
- Subcooling = 2ºC.
- Condensation Temperature **= 43ºC**.
- Isentropic Efficiency = 0.7.
- Heat Losses in the Compressor = 0.1 (10%).

CoolPack was used to obtain the COPs, discharge temperatures, energy consumed (where a utilization factor multiplier of 40% per annum was used), suction line diameters, and mass displacements of all refrigerants except R-32, for which Solkane was used. The service life is based on *the* ASHRAE *Equipment Life Expectancy chart* for reciprocating compressors (ASHRAE, 2024), GWP values by AR-4 IPCC, emission values in kg of CO_2 per kWh were obtained from EPE reports, the leakage and recovery values were obtained from AI-

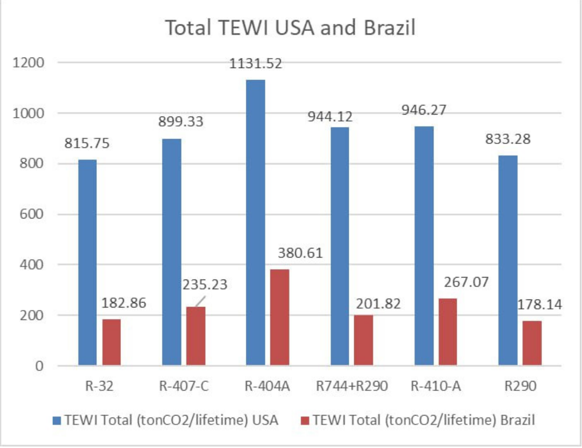
RAH (THE AUSTRALIAN INSTITUTE OF REFRIGERATION, AIR CONDITIONING AND HEATING), and the refrigerant fluid masses were provided by Fapro ETP Laboratories in analyses of existing equipment in the laboratories.

Before analyzing the new TEWI+S+R index, it is important to note that the highest COP was for R-32, the lowest COP was for the combination of R-404-A, the worst refrigerant discharge temperature was for R-410-A, and in Brazil the best TEWI index was for R-290, i.e., if this fluid were the only indicator, it would be the best option in that country, while in the USA the best option would be R-32, proving that the best option in one country is not necessarily the best option in another. Below is a graph comparing the two countries (Brazil and the USA) (Coolpack, 2011) (EPE, 2020).

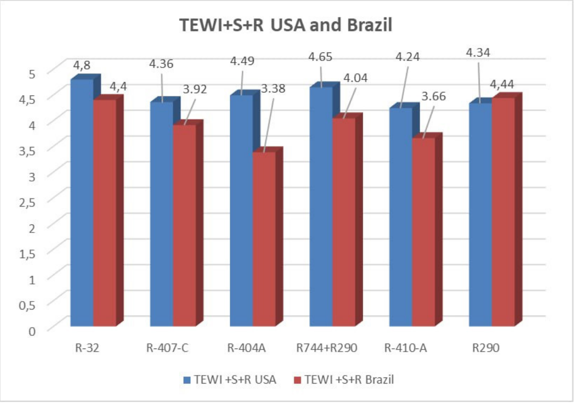
As you can see, the most sustainable source in Brazil makes a big difference compared to the US when it comes to decision-making.

Applying the TEWI+S+R Index, we obtain the following results for Brazil:

As can be seen, the order of fluids in Brazil in relation to TEWI+S+R was R32, R290, R744+R290, R407 C, R410 A, and finally R404 A. The order of fluids in the USA was R32, R4i04 A, R407 C, R290, R744+R 290, and finally R410 A.



Graph 3 – TEWI+S+R USA and BRAZIL



GRAPH 4 – TEWI+S+R BRAZIL

As can be seen from the graphs above, the following can be observed:

Comparative Analysis of Results.

Feasibility of Refrigerants.

1. **R32**:
- **Brazil**: 4.72.
- **USA**: 4.80.
- **Discussion**: R32 shows high viability in both countries. This fluid is known for its good energy efficiency, medium environmental impact (sustainability), safety, and reliability, which justifies its high viability ratings. In the USA, due to the less sustainable matrix factor, the impact of the fluid's GWP has less impact than energy efficiency, a fact that gives R-32 a higher rating in the USA.

2. **R290**:
- **Brazil**: 4.40.
- **USA**: 4.49.
- **Discussion**: R290, or propane, has high viability in both countries. This fluid is appreciated for its low environmental impact and efficiency. However, its flammable properties require additional safety precautions, which creates a greater need for training.

3. **R744+R290**:
- **Brazil**: 4.05.
- **USA**: 4.36.
- **Discussion**: The R744+R290 combina-

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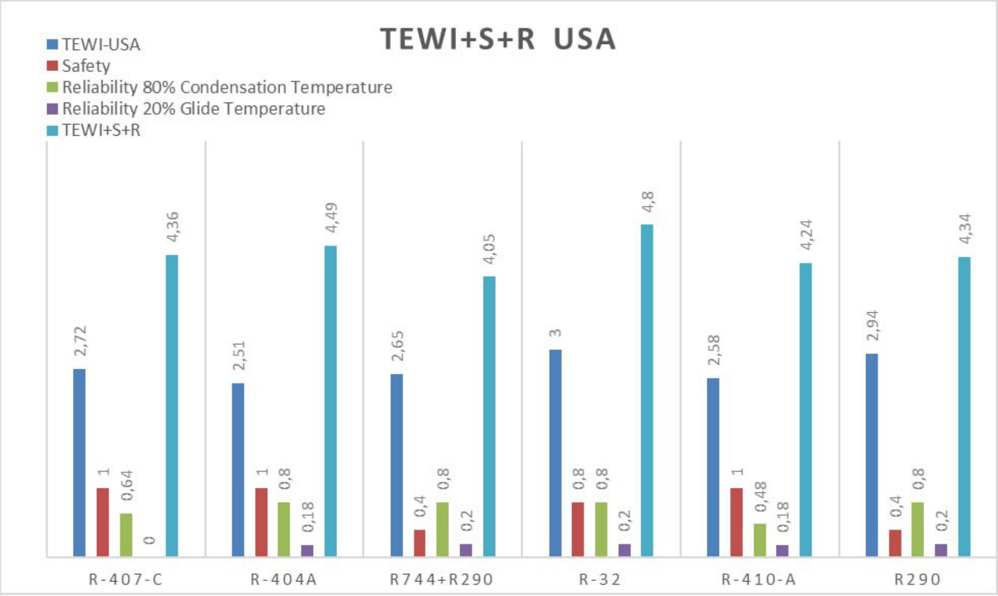

Graph 2 – TEWI+S+R USA

BRAZIL	
FLUID	**TEWI+S+R**
R32	4.72
R290	4.4
R744+R290	4.05
R407C	3.91
R410A	3.66
R404A	3.38

Table 7 – TEWI +S+R Brazil and fluids

USA	
FLUID	**TEWI+S+R**
R32	4.8
R404 A	4.49
R407 C	4.36
R290	4.34
R410A	4.24
R744+R290	4.04

Table 8 – TEWI +S+R USA and fluids

tion, which combines CO_2 and propane, results in good viability, with higher ratings in the USA. The mixture benefits from the properties of both components, offering a good balance between sustainability, safety, and reliability, but it was the least viable option in the USA.

4. **R407 C**:
- **Brazil**: 3.91.
- **USA**: 4.34.
- **Discussion**: R407C, often used as a substitute for R22, has moderate viability, with higher rates in the USA. This fluid in Brazil does not offer a good balance of sustainability, safety, and reliability, but its performance may vary depending on the climate and available technology.

5. **R410A**:
- **Brazil**: 3.66.
- **USA**: 4.24.
- **Discussion**: R410A shows a significant difference in viability between the two countries, being more viable in the US. This fluid is widely used and considered safe and reliable.

6. **R404 A**:
- **Brazil**: 3.38.
- **USA**: 4.04.
- **Discussion**: R404A has the lowest viability in Brazil and moderate viability in the USA. Due to its high environmental impact, there is a global trend to replace it with more sustainable options. In terms of safety and reliability, it is less favorable compared to other fluids.

CONCLUSION

The analysis of refrigerants in the context of the food chain, especially within the "cold chain," is crucial to understanding opportunities for reducing energy consumption and carbon emissions. As discussed, refrigeration systems account for a significant portion of energy consumption and greenhouse gas emissions in the food chain. In this scenario, the choice of refrigerant becomes a strategic decision that directly impacts the sustainability, safety, and reliability of the system.

The results presented show a significant variation in the viability of different refrigerants between Brazil and the US. The R32 refrigerant stands out for its high viability in both countries, with slightly superior performance in the US, possibly due to the less sustainable energy matrix generating a greater emphasis on energy efficiency in the TEWI. This refrigerant combines efficiency, sustainability, safety, and reliability in a balanced manner.

R290, or propane, is also highly viable and appreciated for its low environmental impact. However, its flammable properties require strict safety measures and specialized training, which may limit its applicability in certain contexts. The R744+R290 combination offers good overall viability, benefiting from the properties of CO_2 and propane, but has lower relative viability in the US due to the less sustainable matrix and emphasis on energy efficiency.

R407C and R410A show significant differences between the two countries, with higher viability rates in the US. R404A, on the other hand, has the lowest viability in Brazil and moderate viability in the US, reinforcing the need for its replacement with more sustainable alternatives due to its high environmental impact.

In conclusion, the choice of refrigerant in the food chain must be made considering a balance between sustainability, safety, and reliability. The comparative analysis between Brazil and the US highlights the importance of adapting technological choices to regional specificities, taking into account factors such as the energy matrix, current regulations, and available infrastructure.

FUTURE WORK

To further this analysis, we suggest that future studies conduct a more systemic simulation, such as Life Cycle Assessment (LCA). This approach will allow for the evaluation not only of the efficiency and sustainability of refrigerants, but also of the equivalent mass of substances released into different ecosystems (air, water, and soil) throughout the useful life of refrigeration systems, from the construction of the equipment to its operation and dismantling. In addition, it is recommended to increase the participation of professionals in the research, especially with regard to the relative importance of safety and reliability, ensuring a more comprehensive and robust view of best practices and technological choices in the field of refrigeration (Rossi et al, 2021).

This integrated approach will allow for a better understanding of environmental and operational impacts, contributing to the development of more sustainable and efficient solutions for the global food chain. The implementation of indices that combine decarbonization, efficiency, safety, and reliability will be essential to address environmental challenges and ensure the quality of life and reliability of refrigeration systems in the future.

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